

Tetra-quark Systems in Heavy Mesons*

– $D_{s0}^+(2317)$, $X(3872)$ and related –

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Typical candidates of open- and hidden-charm tetra-quark mesons are studied through their decays and productions, and are compared with conventional mesons. In addition, it is proposed how to confirm experimentally that they are tetra-quark mesons.

I. INTRODUCTION

Tetra-quark mesons can be classified into the following four groups in accordance with the difference of symmetry property of their flavor wavefunctions (wfs.) [1, 2],

$$\{qq\bar{q}\bar{q}\} = [qq][\bar{q}\bar{q}] \oplus (qq)(\bar{q}\bar{q}) \oplus \{[qq](\bar{q}\bar{q}) \oplus (qq)[\bar{q}\bar{q}]\}, \quad (q = u, d, s, c), \quad (\text{I.1})$$

where parentheses and square brackets denote symmetry and anti-symmetry, respectively, of flavor wfs. under exchange of flavors between them. Each term on the right-hand-side (r.h.s.) of Eq. (I.1) is again classified into two groups with $\bar{\mathbf{3}}_c \times \mathbf{3}_c$ and $\mathbf{6}_c \times \bar{\mathbf{6}}_c$ of the color $SU_c(3)$, which can provide colorless tetra-quark states. The force between two quarks [3] is attractive (or repulsive) when they are of $\bar{\mathbf{3}}_c$ (or $\mathbf{6}_c$), so that the $\bar{\mathbf{3}}_c \times \mathbf{3}_c$ state is taken as the lower lying one. Narrow widths of the open- and hidden-charm tetra-quark mesons with $\bar{\mathbf{3}}_c \times \mathbf{3}_c$ can be understood by a small overlap of color and spin wfs. On the other hand, the light scalar mesons [4], $a_0(980)$, $f_0(980)$, $\kappa(800)$ and $\sigma(600)$, in particular, their mass hierarchy and the approximate degeneracy between $a_0(980)$ and $f_0(980)$ can be easily understood in the $[qq][\bar{q}\bar{q}]$ scheme. However, in this case, the corresponding small overlap of color and spin wfs. is not guaranteed, because QCD is non-perturbative and states with $\bar{\mathbf{3}}_c \times \mathbf{3}_c$ and $\mathbf{6}_c \times \bar{\mathbf{6}}_c$ can largely mix with each other at such a low energy scale, so that they are not necessarily narrow. When it is required that the total wfs. of $[qq]$ and (qq) are antisymmetric as in the flavor symmetry limit, their spins are 0 and 1, respectively, because the color wf. is antisymmetric for $\bar{\mathbf{3}}_c$. Therefore, the spin and parity of (at least, dominant components of) $[qq][\bar{q}\bar{q}]$ and $[qq](\bar{q}\bar{q}) \pm (qq)[\bar{q}\bar{q}]$ mesons with $\bar{\mathbf{3}}_c \times \mathbf{3}_c$ are $J^P = 0^+$ and 1^+ , respectively. For the same reason, $(qq)(\bar{q}\bar{q})$ can have $J^P = 0^+, 1^+, 2^+$. However, we ignore it, because no candidate of $(K\pi)_{I=3/2}$ state which can be given by the $(qq)(\bar{q}\bar{q})$ state has been observed [5] in the region $\lesssim 1.8$ GeV in contrast with the theoretical expectation [1]. For more details, see Refs. [6–8].

II. OPEN-CHARM SCALAR MESONS

$D_{s0}^+(2317)$ was discovered [9, 10] through the $D_s^+\pi^0$ channel in inclusive e^+e^- annihilation, while no signal of resonance peak at the same energy in the radiative $D_s^{*+}\gamma$ channel has been observed. Therefore, a severe constraint

$$R(D_{s0}^+(2317))_{\text{CLEO}} = \frac{\Gamma(D_{s0}^+(2317) \rightarrow D_s^{*+}\gamma)}{\Gamma(D_{s0}^+(2317) \rightarrow D_s^+\pi^0)} \Big|_{\text{CLEO}} < 0.059 \quad (\text{II.1})$$

was given by the CLEO [10]. In the case of D_s^{*+} , the ratio of decay rates has been measured as [4]

$$R(D_s^{*+})_{\text{exp}} = \frac{\Gamma(D_s^{*+} \rightarrow D_s^+\pi^0)}{\Gamma(D_s^{*+} \rightarrow D_s^+\gamma)} \Big|_{\text{exp}} = 0.062 \pm 0.008. \quad (\text{II.2})$$

This implies that isospin non-conserving interactions are much weaker than the electromagnetic ones which are much weaker than the isospin conserving strong ones. In fact, assuming that the isospin non-conservation is caused by the $\eta\pi^0$ mixing with the mixing parameter, $\epsilon \simeq 10^{-2}$, as usual [11], and applying the vector meson dominance

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(VMD) [12] to the radiative decay, we can easily reproduce Eq. (II.2), i.e., $R(D_s^{*+}) \simeq 0.06$. Next, when $D_{s0}^+(2317)$ is assigned to the iso-triplet tetra-quark scalar $\hat{F}_I^+ \sim [cn][\bar{s}\bar{n}]_{I=1}$, Eq. (II.1) can be satisfied [7], i.e., $R(D_{s0}^+(2317) = \hat{F}_I^+) \sim (4 - 5) \times 10^{-3} \ll 0.059$. In contrast, if $D_{s0}^+(2317)$ were assigned to an iso-singlet state, (i) the conventional scalar $D_{s0}^{*+} \sim \{c\bar{s}\}$, or (ii) the iso-singlet tetra-quark $\hat{F}_0^+ \sim [cn][\bar{s}\bar{n}]_{I=0}$, Eq. (II.1) could not be satisfied, i.e., (i) $R(D_{s0}^+(2317) = D_{s0}^{*+}) \sim 70 \gg 0.059$, and (ii) $R(D_{s0}^+(2317) = \hat{F}_0^+) \sim 3 \gg 0.059$, as expected above. In this way, it is seen that $D_{s0}^+(2317)$ should be assigned to an iso-triplet state \hat{F}_I^+ . In addition, we have learned that \hat{F}_0^+ and D_{s0}^{*+} decay dominantly into radiative channels. For more details, see Refs. [7] and [8].

Just after the discovery of $D_{s0}^+(2317)$, charm-strange scalar mesons which are degenerate with $D_{s0}^+(2317)$ have been observed not only in the $D_s^+\pi^0$ but also the $D_s^{*+}\gamma$ channels of B decays [13], $Br(B \rightarrow \bar{D}\tilde{D}_{s0}^+(2317)[D_s^+\pi^0]) = (8.5_{-1.9}^{+2.1} \pm 2.6) \times 10^{-4}$ and $Br(B \rightarrow \bar{D}\tilde{D}_{s0}^+(2317)[D_s^{*+}\gamma]) = (2.5_{-1.8}^{+2.0} (< 7.5)) \times 10^{-4}$. (The above naming conventions, $\tilde{D}_{s0}^+(2317)[D_s^+\pi^0]$ and $\tilde{D}_{s0}^+(2317)[D_s^{*+}\gamma]$, have been taken to distinguish the charm-strange scalar mesons observed in B decays from $D_{s0}^+(2317)$ in e^+e^- annihilation.) It should be noted that the above production rate of $\tilde{D}_{s0}^+(2317)[D_s^{*+}\gamma]$ seems to be not much smaller than that of $\tilde{D}_{s0}^+(2317)[D_s^+\pi^0]$, in contrast with the e^+e^- annihilation. We now identify [2] $\tilde{D}_{s0}^+(2317)[D_s^+\pi^0]$ with $D_{s0}^+(2317)$ which has been assigned to \hat{F}_I^+ , and $\tilde{D}_{s0}^+(2317)[D_s^{*+}\gamma]$ is assigned to \hat{F}_0^+ which decays dominantly into the $D_s^{*+}\gamma$, as discussed before. It should be noted that \hat{F}_I^+ and \hat{F}_0^+ are degenerate with each other, in analogy to $a_0(980)$ and $f_0(980)$.

On the other hand, mass of the charm-strange ($C = S = 1$) scalar state has recently been calculated on the lattice [14], and the result has reproduced the measured mass of $D_{s0}^+(2317)$ which has been naturally assigned to the iso-triplet \hat{F}_I^+ in the above. This implies that the mass of the lowest $C = S = 1$ state which can contain not only the scalar $\{c\bar{s}\}$ but also the scalar $[cn][\bar{s}\bar{n}]_{I=0}$, etc. is much lower than that of the scalar $\{c\bar{s}\}$ which has been calculated in the quench approximation (i.e., with no multi-quark component) on the lattice [15], and hence the lowest $C = S = 1$ state cannot be dominated by the $\{c\bar{s}\}$ but could be by the $[cn][\bar{s}\bar{n}]_{I=0}$ component. It would be natural because $a_0(980)$ and $f_0(980)$ have been assigned [1] to the scalar $[ns][\bar{n}\bar{s}]_{I=1}$ and $[ns][\bar{n}\bar{s}]_{I=0}$, and are approximately degenerate with each other while $f_0(1500)$ which is expected [16] to be dominated by the scalar $\{s\bar{s}\}$ is much heavier.

Because $D_{s0}^+(2317)$ has been assigned to \hat{F}_I^+ , its neutral and doubly charged partners, \hat{F}_I^0 and \hat{F}_I^{++} , should exist, although they have not been observed in inclusive e^+e^- annihilation [17]. This implies that their production is suppressed in this process, as was understood within the framework of minimal $q\bar{q}$ pair creation [18]. In this way, it can be understood why experiments did not observe them [19]. In addition, it has been discussed [18, 19] that it is better to search for them in B decays, because the $\tilde{D}_{s0}^+(2317)[D_s^{*+}\gamma]$ as a signal of \hat{F}_0^+ has already been observed in B decays, as mentioned above, and that their production rates are expected to be

$$\begin{aligned} Br(B_u^+ \rightarrow D^- \hat{F}_I^{++}) &\sim Br(B_u^+ \rightarrow \bar{D}^0 \tilde{D}_{s0}^+(2317)[D_s^+\pi^0])_{\text{exp}} \\ &\sim Br(B_d^0 \rightarrow \bar{D}^0 \hat{F}_I^0) \sim Br(B_d^0 \rightarrow D^- \tilde{D}_{s0}^+(2317)[D_s^+\pi^0])_{\text{exp}} \sim 10^{-(3-4)}, \end{aligned} \quad (\text{II.3})$$

because all these decays can be described by similar quark-line diagrams, where more precise values of their measurements have been given in Refs. [13] and [20]. In addition to $\hat{F}_I^{0,+,++}$ and \hat{F}_0^+ , the $[cq][\bar{q}\bar{q}]$ states can have a narrow [2] $\hat{D} \sim [cn][\bar{u}\bar{d}]$. This, as well as the conventional D_0^* , should be found in the observed $D\pi$ enhancement just below the well-known D_2^* peak. Therefore, we now investigate the conventional open-charm scalar mesons, D_0^* and D_{s0}^{*+} , to distinguish them from tetra-quark \hat{D} and \hat{F}_I^+ . The most recent measurement of the $D\pi$ enhancement [21] has provided $m_{D_0} = 2297 \pm 32$ MeV and $\Gamma(D_0) = 273 \pm 74$ MeV. However, it is expected that the above very broad enhancement might have a structure [22] containing a broad conventional scalar D_0^* and a narrow tetra-quark \hat{D} . Although the latter seems to have already been observed as a narrow peak around the lower tail of the $D\pi$ enhancement, it has not seriously been considered in Ref. [21]. Because masses of D_0^* and D_{s0}^{*+} are not definitely known yet, as seen above, we tentatively take $m_{D_0^*} \simeq 2.3$ GeV and $m_{D_{s0}^{*+}} \simeq 2.4$ GeV. The latter seems to be compatible with a prediction on the scalar $\{c\bar{s}\}$ mass in the quench approximation [15], as mentioned before. Taking the flavor $SU_f(4)$ relation for the strong vertices with a 20 – 30 % deviation of spatial wf. overlap from unity (the symmetry limit) [7] and the experimental data [4] on the well-known light scalar K_0^* as the input data, rates for their dominant decays, $D_0^* \rightarrow D\pi$ and $D_{s0}^{*+} \rightarrow DK$, and hence their widths can be estimated to be $\Gamma(D_0^*) \simeq 50 - 60$ MeV and $\Gamma(D_{s0}^{*+}) \simeq 40 - 50$ MeV [22]. The latter leads to $\Gamma(D_{s0}^{*+} \rightarrow D_s^+\pi^0) \simeq 0.2 - 0.3$ keV, and hence $R(D_{s0}^{*+}) \sim 70$, as discussed before. The above $\Gamma(D_0^*)$ is much smaller than the width of the measured broad $D\pi$ enhancement mentioned before. Therefore, we expect that the observed broad $D\pi$ enhancement can have a structure which includes the broad D_0^* and the narrow \hat{D} , as discussed before. The CDF [24] also observed peaks in $D\pi$ mass distributions around 2.2 – 2.3 GeV which can include \hat{D} and D_0^* . Besides, a clear peak in DK mass distribution around 2.4 GeV which is degenerate with D_{s0}^{*+} has been observed by the CLEO [23]. Because these peaks have been taken away as false peaks, however, we hope that experiments re-analyze more precisely the above mass distributions and find true signals of D_{s0}^{*+} , D_0^* and \hat{D} behind the false peaks.

III. HIDDEN-CHARM MESONS

$X(3872)$ was discovered in the $\pi^+\pi^-J/\psi$ mass distribution by the Belle [25], and then confirmed [26] by the CDF, D0 and Babar. (Hereafter, we describe J/ψ as ψ , for simplicity.) Experiments [27–29] favor 1^{++} as the J^{PC} of $X(3872)$. However, it decays into two different final states with opposite G -parities,

$$R \equiv \frac{Br(X(3872) \rightarrow \pi^+\pi^-\pi^0\psi)}{Br(X(3872) \rightarrow \pi^+\pi^-\psi)} = 1.0 \pm 0.4 \pm 0.3. \quad (\text{III.1})$$

This is puzzling because the well-known strong interactions conserve G -parity. In addition, the Belle [25] and CDF [30] have noted that the decay $X(3872) \rightarrow \pi^+\pi^-\psi$ proceeds through $\rho^0\psi$. If the isospin were conserved in the decay, there should exist charged partners of $X(3872)$, in contradiction to a negative result from an experimental search [31]. This would imply that $X(3872)$ is an iso-singlet state, and hence the isospin conservation does not work in the $X(3872) \rightarrow \rho^0\psi \rightarrow \pi^+\pi^-\psi$ decay. Besides, the Belle [32] has suggested that the $X(3872) \rightarrow \pi^+\pi^-\pi^0\psi$ decay proceeds through the sub-threshold $X(3872) \rightarrow \omega\psi$. If isospin is conserved in this decay, $X(3872)$ would be an iso-singlet state. This is consistent with the above negative result on the search for its charged partners.

Although various approaches [33] to solve the above puzzle have been proposed, they are unnatural, because the phenomenologically well-known $\omega\rho^0$ mixing [4, 34] which can play an important role in the isospin non-conservation under consideration [35] has not been considered. Under the assumption that the above isospin non-conservation is caused by the $\omega\rho^0$ mixing with a mixing parameter [35] $|g_{\omega\rho}| \simeq 3.4 \times 10^{-3} \text{ GeV}^2$, the isospin non-conserving $X(3872) \rightarrow \rho^0\psi$ decay proceeds through two steps; the isospin conserving $X(3872) \rightarrow \omega\psi$ and the subsequent $\omega\rho^0$ mixing, $X(3872) \rightarrow \omega\psi \rightarrow \rho^0\psi$. Here we consider the $X(3872) \rightarrow \gamma\psi$ in place of the $X(3872) \rightarrow \pi^+\pi^-\pi^0\psi$ decay in Eq. (III.1), because the kinematics of the former is much simpler than the latter. As the result, we shall see below that existing data on the ratio

$$R_X^\gamma \equiv \frac{Br(X(3872) \rightarrow \gamma\psi)}{Br(X(3872) \rightarrow \pi^+\pi^-\psi)} \quad (\text{III.2})$$

will select a realistic interpretation of $X(3872)$. When the above assumption is combined with the VMD [12], the $X(3872) \rightarrow \gamma\psi$ decay would proceed as

$$X(3872) \rightarrow \omega\psi \rightarrow \gamma\psi \quad \text{and} \quad X(3872) \rightarrow \omega\psi \rightarrow \rho^0\psi \rightarrow \gamma\psi. \quad (\text{III.3})$$

However, the contribution of the second decay is much smaller than that for the first one because $|g_{\omega\rho}/m_\omega^2| \ll 1$, while the role of the ρ^0 pole can be strongly enhanced [35] in the $X(3872) \rightarrow \omega\psi \rightarrow \rho^0\psi \rightarrow \pi^+\pi^-\psi$ because $|g_{\omega\rho}/(m_\omega^2 - m_\rho^2)| \gg |g_{\omega\rho}/m_\omega^2|$.

If $X(3872)$ were an axial-vector charmonium, the radiative decay under consideration could have an extra contribution through the ψ pole, $X(3872) \rightarrow \psi\psi \rightarrow \gamma\psi$, as the dominant one. In contrast, when $X(3872)$ is a tetra-quark state like [36] $\{[c\bar{n}](\bar{c}\bar{n}) + (c\bar{n})[\bar{c}\bar{n}]\}$ arising from the last term on the r.h.s. of Eq. (I.1), such a contribution is suppressed because of the OZI rule [37]. Therefore, we study if the above isospin non-conservation can be reconciled with the measured ratios, $(R_X^\gamma)_{\text{Belle}} = 0.14 \pm 0.05$ [32] and $(R_X^\gamma)_{\text{Babar}} = 0.33 \pm 0.12$ [38].

In the above $\omega\rho^0$ mixing model [35], the value of R_X^γ in Eq. (III.2) can be estimated without any unknown parameter, if $X(3872)$ is a tetra-quark system, i.e., $(R_X^\gamma)_{\text{tetra}} \simeq (R_X^\gamma)_{\text{Babar}} \sim (R_X^\gamma)_{\text{Belle}}$, because all the parameters involved in the decays can be estimated by using the existing experimental data [4], except for the $X\omega\psi$ coupling $g_{X\omega\psi}$ which can be canceled by taking the ratio of decay rates in Eq. (III.2). (The γV coupling strengths $X_V(0)$, $V = \rho^0, \omega, \phi, \psi$, on the photon-mass-shell have already been estimated [39].) In addition, the measured production of prompt $X(3872)$ seems to favor a more compact object (i.e., a tetra-quark meson) over a loosely bound meson-meson molecule [40]. In contrast, if $X(3872)$ were a charmonium, the estimated ratio would be much larger than the observation, i.e., $(R_X^\gamma)_{c\bar{c}} \gg (R_X^\gamma)_{\text{tetra}} \simeq (R_X^\gamma)_{\text{Babar}} \sim (R_X^\gamma)_{\text{Belle}}$, because of the OZI rule. Therefore, the existing data on R_X^γ favor a tetra-quark interpretation of $X(3872)$, although a small mixing of χ'_{c1} would be needed to understand the measured ratio [38], $\Gamma(X \rightarrow \gamma\psi')/\Gamma(X \rightarrow \gamma\psi)|_{\text{Babar}} = 3.4 \pm 1.4$. See Ref. [35] for more details.

IV. SUMMARY

Comparing the ratio of rates for the $D_{s0}^+(2317) \rightarrow D_s^{*+}\gamma$ decay to the $D_s^+\pi^0$ with the experimental constraint Eq. (II.1), we have seen that assigning $D_{s0}^+(2317)$ to \hat{F}_I^+ is favored by experiments. In this case, \hat{F}_I^0 , \hat{F}_I^{++} and \hat{F}_0^+ should exist and be observed. However their production through inclusive $e^+e^- \rightarrow c\bar{c}$ is suppressed, so that their observation is likely to be quite difficult, although $D_{s0}^+(2317)$ itself has already been observed. Therefore, we have

discussed that, to search for them, B decays would be much better. In fact, an indication of $\hat{F}_0^+ = \tilde{D}_{s0}^+(2317)[D_s^{*+}\gamma]$ has already been observed by the Belle [13].

We have studied the ratio of decay rates R_X^γ in Eq. (III.2), assuming that the isospin non-conservation is caused by the phenomenologically well-known $\omega\rho^0$ mixing. As the result, we have seen that the existing data on R_X^γ and production of the prompt $X(3872)$ favor a tetra-quark interpretation of $X(3872)$ like $\{[cn](\bar{c}\bar{n}) + (cn)[\bar{c}\bar{n}]\}_{I=0}$ over a meson-meson molecule and a charmonium. To confirm the above interpretation, observation of $\{[cn](\bar{c}\bar{n}) - (cn)[\bar{c}\bar{n}]\}_{I=0}$ with a mass close to $m_{X(3872)}$ in the $\pi^0\pi^0\psi$ channel is awaited.

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